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**PATH-INTEGRAL APPROACH IN A CHIRAL
QUARK-DIQUARK MODEL TO THE NUCLEON
STRUCTURE AND INTERACTIONS**

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We study the structure of the nuclear force by using a path-integral hadronization approach in a chiral quark-diquark model. After the construction of the chiral quark-diquark model, we hadronize it to obtain a meson-baryon Lagrangian. The effective meson-baryon Lagrangian incorporates chiral symmetry and the composite description of the mesons and baryons. Using the effective meson-baryon Lagrangian we investigate the structure of the nuclear force in the simple case of neglecting the axial-vector diquark. It is shown that the meson-baryon Lagrangian contains two kinds of the nuclear force; the meson-exchange interaction and a quark-diquark loop interaction. It is also shown that the quark-diquark loop interaction consists of the scalar and vector interactions. The properties of these interactions are discussed.

1 Introduction

The origin of the short range repulsion in the nucleon-nucleon(NN) interaction is a long-standing problem. The NN interaction below the meson production threshold is phenomenologically well understood, having been fit to the phase shift analysis, but its microscopic understanding is still needed. While the long range part is well described by the meson exchange picture, there are several different approaches to the description of the short range part, including meson exchange and quark exchange^{1,2,3,4,5,6}. Because in the short range region the two nucleons have a substantial spatial overlap, it is commonly assumed that the internal structure of the nucleon gives a

sizable contribution to the nuclear force at such short distances. To obtain a comprehensive understanding of the nuclear force from the short to long range distances, models which incorporate both the meson exchange and the internal structure of the nucleon are needed.

In a recent publication, we studied the structure of the nuclear force using the path-integral hadronization approach to a chiral quark-diquark model⁷. This method incorporates two aspects of chiral symmetry, which naturally describes the pion exchange interaction, and of the internal structure of hadrons. This method employs an extended model of the Nambu-Jona-Lasinio type⁸ with the interactions that are not only of the quark-antiquark type but also of the quark-diquark type⁹. The quarks and diquarks were integrated out to generate an effective Lagrangian for mesons and baryons while maintaining important symmetries, such as the gauge and chiral symmetries. The hadron structure was then described in terms of its constituents: a quark and an antiquark for mesons and a quark and a diquark for baryons. It was also pointed out that the resulting effective Lagrangian contains various interactions among hadrons, such as meson-meson, meson-baryon and baryon-baryon interactions.

In our model, all components of the NN force are contained in an effective Lagrangian that is written in a concise form as a trace-log. Then, the expansion of the trace-log terms produces an NN force that is described as meson exchanges at long and medium ranges and quark-diquark exchanges at short ranges. The latter was then shown to contain various types of non-local interactions, including a scalar iso-scalar type and a vector iso-scalar type. We evaluated the properties of the scalar and vector type interactions; their ranges, effective masses and strengths.

In this paper, we report the results of the study of the nuclear force in the simple framework where the axial-vector diquark is neglected. In the previous work, we suggested that the neglecting the axial-vector diquark does not affect to the size of the nucleon, hence we can properly evaluate the ranges of the NN interactions with only scalar diquarks.

We organize this paper as follows. In § 2, we briefly give the derivation of the trace-log formula in the path-integral hadronization of the NJL model with quark-diquark correlations. In § 3, terms containing the NN interaction are investigated in detail, where the general structure of the NN amplitude is presented. We present a sample numerical calculation for the case in which there is only a scalar diquark. The present study of the NN interaction is not quantitatively complete, but it will be useful in demonstrating some important aspects of the nuclear force, in particular that the range of the short range interaction is related to the intrinsic size of the nucleon. The final section is

devoted to a summary.

2 Effective Lagrangian for mesons and nucleons

We now briefly review the method to derive an effective Lagrangian for mesons and nucleons from a quark and diquark model of chiral symmetry following the previous work of Abu-Raddad et al ⁹. We start from the NJL Lagrangian,

$$\mathcal{L}_{\text{NJL}} = \bar{q}(i\not{\partial} - m_0)q + \frac{G}{2} [(\bar{q}q)^2 + (\bar{q}i\gamma_5\vec{\tau}q)^2] . \quad (1)$$

Here, q is the current quark field, $\vec{\tau}$ represents the isospin (flavor) Pauli matrices, G is a dimensional coupling constant, and m_0 is the current quark mass. In this paper, we set $m_0 = 0$ i.e. we work in the chiral limit. As usual, the NJL Lagrangian is bosonized by introducing meson fields as collective auxiliary fields in the path-integral method ^{10,11,12}. At an intermediate step, we find the following Lagrangian:

$$\mathcal{L}'_{q\sigma\pi} = \bar{q}(i\not{\partial} - (\sigma + i\gamma_5\vec{\tau} \cdot \vec{\pi}))q - \frac{1}{2G}(\sigma^2 + \vec{\pi}^2) . \quad (2)$$

Here σ and $\vec{\pi}$ are scalar-isoscalar sigma and pseudoscalar-isovector pion fields, as generated from $\sigma \sim \bar{q}q$ and $\vec{\pi} \sim i\bar{q}\vec{\tau}\gamma_5q$, respectively. For our purpose, it is convenient to work in a non-linear basis rather than the linear one ^{13,14}. This is realized through the chiral rotation from the current (q) to constituent (χ) quark fields:

$$\chi = \xi_5 q, \quad \xi_5 = \left(\frac{\sigma + i\gamma_5\vec{\tau} \cdot \vec{\pi}}{f} \right)^{1/2}, \quad (3)$$

where $f^2 = \sigma^2 + \vec{\pi}^2$. Thus, we find

$$\mathcal{L}'_{\chi\sigma\pi} = \bar{\chi}(i\not{\partial} - f - \not{a} - \not{a}\gamma_5)\chi - \frac{1}{2G}f^2, \quad (4)$$

where

$$v_\mu = -\frac{i}{2}(\partial_\mu\xi^\dagger\xi + \partial_\mu\xi\xi^\dagger), \quad a_\mu = -\frac{i}{2}(\partial_\mu\xi^\dagger\xi - \partial_\mu\xi\xi^\dagger) \quad (5)$$

are the vector and axial-vector currents written in terms of the chiral field,

$$\xi = \left(\frac{\sigma + i\vec{\tau} \cdot \vec{\pi}}{f} \right)^{1/2}. \quad (6)$$

The Lagrangian (4) describes not only the kinetic term of the quark, but also quark-meson interactions such as the Yukawa one, Weinberg-Tomozawa one etc.

In the model we consider here, we introduce diquarks and their interaction terms with quarks. We assume local interactions between quark-diquark pairs to generate the nucleon field. As suggested by a method of constructing a local nucleon field, it is sufficient to consider two types of diquarks, a scalar, isoscalar diquark, D , and an axial-vector, isovector diquark, \vec{D}_μ ¹⁵. In this work, we consider only the scalar diquark. Hence, our microscopic Lagrangian for quarks, diquarks and mesons is given by

$$\mathcal{L} = \bar{\chi}(i\partial - f - \not{p} - \not{p}\gamma_5)\chi - \frac{1}{2G}f^2 + D^\dagger(\partial^2 + M_S^2)D + \tilde{G} \bar{\chi}D^\dagger D\chi. \quad (7)$$

In the last term, \tilde{G} is a coupling constant for the quark-diquark interaction.

Now, the hadronization procedure can be carried out straightforwardly by introducing the baryon fields as auxiliary fields, $B \sim D\chi$, and by eliminating the quark and diquark fields in (7). The final result is written in a compact form as⁹

$$\mathcal{L}_{\text{eff}} = -\frac{1}{2G}f^2 - i \text{tr} \ln(i\partial - f - \not{p} - \not{p}\gamma_5) - \frac{1}{\tilde{G}} \bar{B}B + i \text{tr} \ln(1 - \mathcal{S}). \quad (8)$$

Here, the trace is taken over space-time, color, flavor and Lorentz indices, and the operator \mathcal{S} is defined by

$$\mathcal{S} = \Delta^T \bar{B} S B, \quad (9)$$

In this equation, $S = (i\partial - f - \not{p} - \not{p}\gamma_5)^{-1}$, $\Delta = (\partial^2 - M_S^2)^{-1}$ are the propagators of the quark and scalar diquark, respectively, and transposed diquark propagators, as denoted by the superscript T , are employed. Note that the quark propagator S contains the interactions with pions. Through this interactions, the nucleon-pion interactions are obtained. Though the effective meson-nucleon Lagrangian (8) looks simple, it contains many important physical ingredients when the trace-log terms are expanded:

- It generates a meson Lagrangian in a chirally symmetric manner. Up to fourth order in the meson fields, it produces precisely the Lagrangian of the linear sigma model with the realization of the spontaneous breaking of chiral symmetry. Hence, the vacuum expectation value f turns out to be the pion decay constant f_π .
- From the second trace-log term, a nucleon effective Lagrangian is derived. In a previous paper, the kinetic term of the nucleon was investigated, and the mass of the nucleon was computed at the one-loop level⁹.
- In the nucleon effective Lagrangian, meson-nucleon couplings appear through the diagrams, as shown in Fig. 1. Their strengths and form

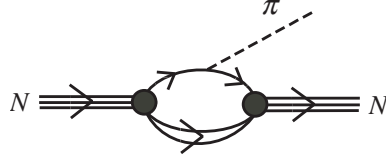


Figure 1. A quark-diquark one-loop diagram for the meson-nucleon Yukawa vertex. The solid, double, dotted and triple lines represent the quark, diquark, meson and nucleon, respectively. The blobs represent the three point quark-diquark-baryon interaction.

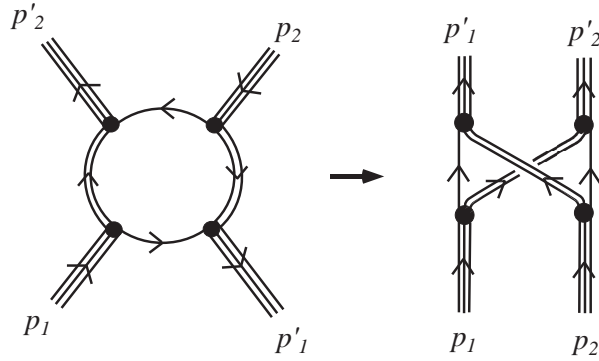


Figure 2. A loop diagram for the NN interaction (left) and the equivalent diquark exchange diagram.

factors can be computed with the use of the underlying quark-diquark dynamics. Using these vertices, meson-exchange interactions are constructed. the photon-nucleon couplings are also obtained in the same manner. The radii and magnetic moments were evaluated without the axial-vector diquark^{9,7}.

- There are diagrams that contain many nucleon fields. For instance, NN interactions are expressed as one-loop diagrams, as shown in Fig. 2. This term describes the short range part of the NN interaction. In this paper, we focus our attention mostly on the NN interaction derived from the one-loop diagrams.

3 Short range interaction

We evaluate the short range interaction described by the quark-diquark loop, as shown in Fig. 2. Using the interaction vertices given in Eq. (9), it is straightforward to compute the amplitude for the quark-diquark loop:

$$\mathcal{M}_{NN} = -iN_c Z^2 \frac{d^4 k}{(2\pi)^4} \times \frac{\bar{B}(p'_1)(\not{k} + m_q)B(p_1)\bar{B}(p'_2)(\not{p}_2 - \not{p}'_1 + \not{k} + m_q)B(p_2)}{[(p_1 - k)^2 - M_S^2][k^2 - m_q^2][(p'_1 - k)^2 - M_S^2][(p_2 - p'_1 + k)^2 - m_q^2]}. \quad (10)$$

where N_c is the number of colors and Z is the wave-function renormalization constant. In this equation, the momentum variables are assigned such that p_1 and p'_1 (p_2 and p'_2) are for the pair of contracted baryon fields, $\bar{B}(p'_1) \cdots B(p_1)$ ($\bar{B}(p'_2) \cdots B(p_2)$), and the momentum transfer is defined by $q = p'_1 - p_1$. Note that the momentum q is carried by the diquark pair. The amplitude defined in this way can be interpreted as a direct term in the local potential approximation. When computing physical quantities such as phase shifts, we need to include the exchange term that is obtained by interchanging the momentum variables $p'_1 \leftrightarrow p'_2$. Although the one-loop integral (10) converges when the scalar diquark is included, we keep the counter terms of the Pauli-Villars regularization. Because our model is a cut-off theory with a relatively small cutoff mass, $\Lambda_{PV} = 0.63$ GeV, the counter-terms play a significant role. However, because we include only the scalar diquark, we do not attempt to make a comparison at the quantitative level. Rather, in the following, we study some basic properties of the amplitude itself, mostly the interaction ranges extracted from Eq. (10).

Let us evaluate the integral in the center-of-mass system for elastic scattering:

$$p_1 = (E_{\vec{p}}, \vec{p}), \quad p_2 = (E_{\vec{p}}, -\vec{p}), \\ p'_1 = (E_{\vec{p}'}, \vec{p}'), \quad p'_2 = (E_{\vec{p}'}, -\vec{p}'), \quad |\vec{p}| = |\vec{p}'|.$$

To proceed, we write the amplitude (10) as

$$\mathcal{M}_{NN} = F_S(\vec{P}, \vec{q})(\bar{B}B)^2 + F_V(\vec{P}, \vec{q})(\bar{B}\gamma_\mu B)^2 + \cdots, \quad (11)$$

where

$$\vec{P} = \vec{p}' + \vec{p}, \quad \vec{q} = \vec{p}' - \vec{p}. \quad (12)$$

Roughly speaking, the q -dependence expresses the interaction range in the t -channel, whose Fourier transform is interpreted as the r -dependence of the

local potential, while the P -dependence expresses the non-locality of the interaction.

In Eq. (11), we have defined the coefficients F_S and F_V as scalar and vector interactions, respectively. The ellipsis in Eq. (11) then include terms involving external momenta p_i , such as $(\bar{B}\Gamma(p_i)B)(\bar{B}B)$ and $(\bar{B}B)(\bar{B}\Gamma(p_i)B)$, where $\Gamma(p_i)$ are 4×4 matrices involving p_i . These momentum dependent terms are, however, expected to play a less important role than the dominant components of the scalar and vector terms, as in boson exchange models. Therefore, we consider here the corresponding terms of scalar and vector types. It turns out that the interaction coefficients defined in this way are attractive for F_S and repulsive for F_V .

As anticipated, the amplitude is highly non-local, as the quark-diquark loop diagram implies. As a matter of fact, the interaction range for the diquark exchange in the t -channel is shorter than that for the quark exchange in the s -channel. This is shown explicitly in Fig. 3. Nevertheless, we proceed further and carry out an expansion in \vec{P} . We obtain

$$F_i(\vec{P}, \vec{q}) = F_i(\vec{P}, \vec{q})|_{\vec{P}=0} + \vec{P} \cdot \frac{\partial}{\partial \vec{P}} F_i(\vec{P}, \vec{q})|_{\vec{P}=0} + \cdots, \quad (13)$$

where i stands for S or V . The resulting \vec{q} dependent function, in particular the first term, can be interpreted as the Fourier transform of a local potential as a function of the relative coordinates $\vec{r} = \vec{x}_1 - \vec{x}_2$. Then, the general structure of the NN potential can be studied by performing the non-relativistic reduction of the amplitude, Eqs. (11) and (13). It contains central, spin-orbit and tensor components that accompany functions of non-locality \vec{P} .

We now discuss the functions F_S and F_V in Eq. (11) for the leading-order terms of Eq. (13). Because we cannot write the resulting q dependent functions in an analytic form, we have carried out numerical calculations employing several different values of \tilde{G} parameter for different binding energies and the size of the quark-diquark bound state.

At this point, we explain our parameters and the regularization scheme. We follow the scheme presented in Ref. ⁹, except for the treatment of \tilde{G} . The Λ_{PV} is the cutoff mass of the Pauli-Villars method used in this work to regularize divergent integrals. We note that our model is unrenormalizable. The NJL coupling constant G and the cut-off mass Λ_{PV} are fixed to generate the constituent quark mass m_q and the pion decay constant through the NJL gap equation in the meson sector ^{12,16,17}. The mass of the scalar diquark M_S is determined in the NJL model by solving the Bethe-Salpeter equation in the diquark channel ^{18,19}. Then, we have one free parameter, the quark-diquark coupling constant \tilde{G} . The strength of \tilde{G} controls the binding or size

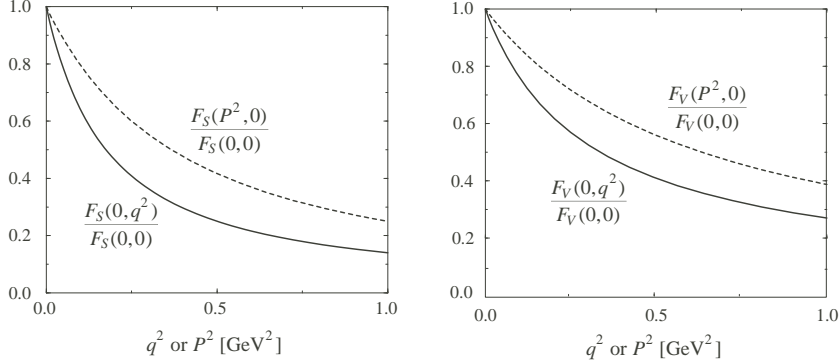


Figure 3. Normalized scalar and vector form factors as functions of $q^2 = |\vec{q}|^2$ with fixed $\vec{P} = 0$ (solid curve) and those of $P^2 = |\vec{P}|^2$ with fixed $\vec{q} = 0$ (dashed curve). The calculations were performed using the parameter set given in Table 1.

Table 1. Model parameters.

	M_N [GeV]	m_q [GeV]	M_S [GeV]	Λ_{PV} [GeV]	\tilde{G} [GeV $^{-1}$]	$\langle r^2 \rangle^{1/2}$ [fm]
set I	0.94	0.39	0.60	0.63	271.0	0.77
set II	0.85	0.39	0.60	0.63	445.9	0.54

of the nucleon and generates the mass of the nucleon M_N . Then we perform numerical calculations by varying the coupling constant \tilde{G} . In Table 1, we list typical parameter values as used in Ref. 7.

First, we determine the strengths of the interactions by extracting coupling constant squares g_i^2 as

$$|F_i(0, 0)| = \frac{g_i^2}{m_i^2}, \quad g_i > 0, \quad (14)$$

where the effective meson masses m_i are evaluated using the inverse of (15) and are plotted in Fig. 6. The results are displayed in Fig. 4 as functions of the size of the nucleon, $\langle r^2 \rangle^{1/2}$. The coupling strengths can be compared with the empirical values $g_S \sim 10$ and $g_V \sim 13$ ². The present results are strongly dependent on $\langle r^2 \rangle$. When only a scalar diquark is included, the scalar interaction becomes much stronger than the vector interaction. Phenomenologically, the vector (omega meson) coupling is stronger than the scalar (sigma meson)

coupling.

We should comment on the effect of the axial-vector diquark. The loop integral containing the axial-vector diquarks diverges and has a large numerical value even when it is regularized. Therefore, it significantly affects the absolute values of the loop integrals as well as that of the baryon self energy, which is necessary to extract the normalization factor Z . Therefore, it is expected that the strengths are affected significantly, but the ranges and the corresponding masses, which are computed from the momentum dependence of the normalized loop integrals, are not affected much.

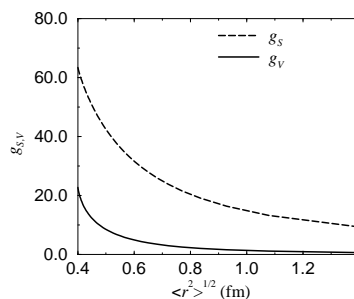


Figure 4. Scalar and vector coupling constants as functions of the nucleon size, $\langle r^2 \rangle^{1/2}$.

Let us discuss the interaction ranges. In Fig. 5, we show the q -dependence of the zeroth order coefficients in Eq. (13) for three different sizes of the nucleon. It is obvious from Fig. 5 that as the size of the nucleon becomes smaller the interaction ranges become shorter. More quantitatively, we define the interaction ranges R_i by

$$R_i^2 \equiv -6 \frac{1}{F_i(q^2)} \frac{\partial F_i}{\partial q^2} \Big|_{q^2 \rightarrow 0}, \quad (15)$$

which are related to the mass parameters of the interaction ranges as $m_i \equiv \sqrt{6}/R_i$. It is interesting that the range (and hence mass) parameters of the interactions are approximately proportional to the size of the nucleon $\langle r^2 \rangle^{1/2}$, as shown in Fig. 6. When the parameter set I listed in Table 1 is used, the mass parameters are about 650 MeV and 800 MeV for the scalar and vector interactions, respectively, which are very close to the masses of the sigma and omega mesons. If, however, we use the parameter set II for a nucleon size of about 0.5 fm, then the two masses become $m_S \sim 800$ MeV and $m_V \sim 1000$

MeV.

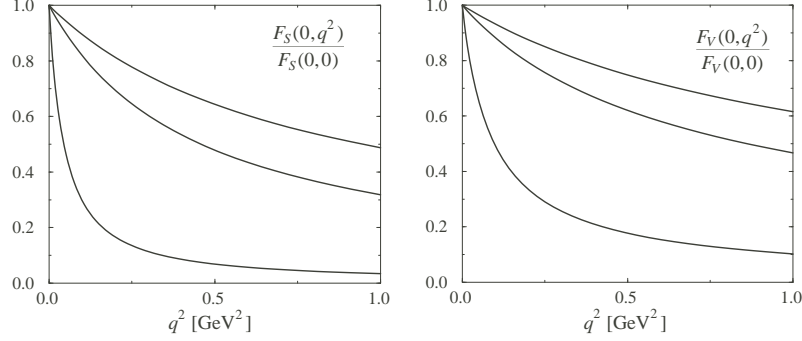


Figure 5. The scalar (left panel) and vector (right panel) form factors $F_{S,V}(q^2, P^2=0)/F_{S,V}(q^2=0, P^2=0)$, (form factors are normalized to 1 at $q^2=0$). The curves correspond to $M_N=0.98, 0.85, 0.70$ GeV from bottom to top.

In the present analysis, apart from the absolute values of the interaction strengths, the interaction ranges for the scalar and vector interactions have been produced appropriately with the quark-diquark loop diagram. One question concerns the small but non-negligible difference between the ranges in the scalar and vector channels, which is consistent with empirical results. This can be roughly understood from the dimensionality of the loop integral. As

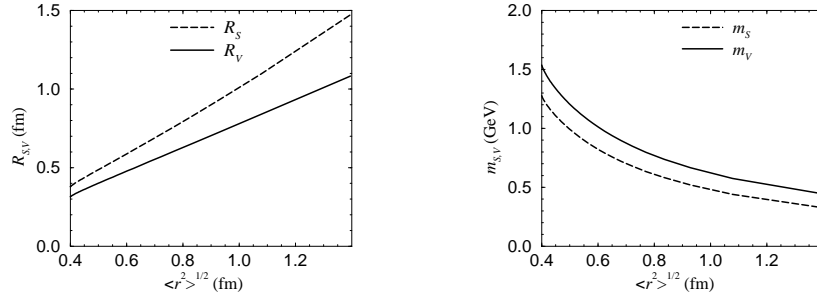


Figure 6. The interaction range R_i (left panel) and the corresponding mass parameter m_i (right panel) as functions of the nucleon size (distribution of a quark and a diquark).

seen from Eq. (10), the integrand for the vector interaction is of higher order with respect to the loop momentum than the scalar interaction. Because of this, the vector part reflects shorter distant dynamics and produces a shorter interaction range.

Although we have obtained reasonable results for the interaction ranges, the short range part of the nuclear force must be repulsive. Hence, current approach is not satisfactory. We believe that the inclusion of the axial-vector diquark will give a sizable contribution to the short range repulsion because the quark-axial-vector diquark-baryon vertex is basically spin-spin type interactions, and thus correct this shortcoming of our present approximation.

4 Summary

In this paper we have studied the NN interaction using a microscopic theory of quarks and diquarks. Nucleons were described as quark-diquark bound states. The quark and diquark degrees of freedom were integrated out using the path-integral method, and an effective Lagrangian was derived for mesons and baryons. The resulting trace-log formula contains various meson and nucleon interaction terms, including the NN interaction in the short range region expressed as a quark-diquark loop. Hence, the NN interaction can be naturally expressed as meson exchanges at long ranges and quark or diquark exchanges at short ranges.

For short range interactions, we have computed a quark-diquark loop corresponding to the direct term of the two-nucleon interaction. The resulting interaction is highly nonlocal. We have extracted scalar and vector type interactions in the local potential approximation. It turns out that the scalar term is attractive, while the vector is term repulsive.

In the present paper our numerical calculations contained only scalar diquarks, as a first step toward a full calculation. Therefore, we have concentrated our study mostly on the interaction ranges or, equivalently, the masses, because the magnitude of strengths is affected by the axial-vector diquark. On the other hand, the interaction ranges were better studied in the present study including only scalar diquarks, reflecting the size of the nucleon. Consequently, the mass parameters of the interaction ranges for the scalar and vector interactions were found to be about 650 MeV for the scalar type and about 800 MeV for the vector type, once again with the nucleon size set at 0.77 fm. Hence in our model, the scalar-isoscalar interaction emerges from the quark-diquark loop at an energy scale similar to that of the sigma and omega meson exchanges. The existence of the two components in the nuclear force, boson exchanges and quark-diquark exchanges, is a general feature when we

consider a model of nucleons that is composed of a quark (and diquark) core surrounded by meson cloud.

The present result encourages us to further study baryon properties by extending the model to include the axial-vector diquark. We have already started such a study. When the axial-vector diquark is included, loop integrals diverge more strongly than in the case of the scalar diquark, due to the massive vector nature of the propagator. Although this causes the numerical study to be more complicated than in the present case, this work is in progress.

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